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Modeling Ballistic Live-Fire Events Trilogy

by Paul H. Deitz, Richard Saucier, and William E. Baker

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Modeling Ballistic Live-Fire Events Trilogy

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Abstract

This report contains three independent but closely related papers which were written to address a request by Mr. Walter Hollis, Deputy Undersecretary of the Army, Operations Research. Each paper was presented at a symposium in FY96 and was published in the respective symposium proceedings: 1] "A V/L Taxonomy for Analyzing Ballistic Live-Fire Events," 46th Annual Bomb and Warhead Technical Symposium, held at Naval Postgraduate School, Monterey, CA, May 13-15, 1996; 2] "Modeling Ballistic Live-Fire Events," 7th Annual TARDEC Symposium, held at Naval Postgraduate School, Monterey, CA, March 26-28, 1996; and 3] "Developments in Modeling Ballistic Live-Fire Events," 16th International Symposium on Ballistics, held in San Francisco, CA, September 23-28, 1996. In combination, this trilogy documents the current state-of-the-art in Army capabilities and specifies the future directions for modeling live-fire events in support of requirements specified in United States Code, Title 10, Section 2366, Chapter 139, National Defense Authorization Act for FY87, "Live Fire Testing."

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A V/L TAXONOMY FOR ANALYZING BALLISTIC LIVE-FIRE EVENTS

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Paper presented at the 46th Annual Bomb & Warhead Technical Symposium, held at the Naval Postgraduate School, Monterey, CA, May 13-15, 1996.

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ABSTRACT

Beginning with World War II and its aftermath, the area of ballistic vulnerability/lethality (V/L) was first defined as a specific discipline within the field of ballistics. As the field developed, various practices and metrics emerged. In some cases metrics were developed which were abstractly useful but, for example, bore no direct relationship to field observables. In the last decade, as the issues of live-fire strategies and model VV&A have gained importance, increased attention has been focussed on V/L with the intent of bringing greater rigor and clarity to the discipline. In part this effort has taken the form of defining a *V/L Taxonomy*, which, in essence, is a method of decomposing a series of concatenated complex processes into separable, less-complex ones, each with certain properties and relationships, one to another. This paper attempts to summarize these efforts and illuminate their relevance to the V/L endgame activities so critical to modern weapons analyses.

1. Purpose

Insight into the processes of vulnerability and lethality can be gained through use of what is now called the *Vulnerability/Lethality (V/L) Taxonomy.*[∞] It was first generated[1] as a by-product of a program to improve the quality of Live-Fire (LF) Abrams vulnerability modeling. In essence, the V/L Taxonomy provides a method to decompose the elements of V/L into a sequence of simpler constituent parts. As we will see, the parts relate to each other in a specific processing order, but are fundamentally different, one from the other, and each has its unique and appropriate use in the general scheme of V/L assessment.

2. V/L Taxonomy *via* a Combat Analogue

The V/L Taxonomy can probably best be introduced *via* a description in terms of its physical and engineering processes. Figure 1 illustrates such a view of the Taxonomy. The process structure is illustrated with a missile attacking an aircraft, although this process is applicable for any ballistic threat against any target.[†] The cartoons at the center of Fig. 1 represent alternately *Levels*, indicated on the left, connected by *Transformation* processes, indicated on the right.

We start with an explanation of the process of Vulnerability using Fig. 1. In conventional vulnerability, it is normal practice to assume a warhead hit (or ballistic interaction) with a target *as a given*. It is useful to think in this context of a LF test. **Level 1]** represents a complete geometric and material description of a threat (here a missile), a target

∞ See Appendix A for standard definitions of Lethality, Vulnerability, and Survivability.

1. Paul H. Deitz and Aivars Ozolins, *Computer Simulations of the Abrams Live-Fire Field Testing,* **Proceedings of the XXVII Annual Meeting of the Army Operations Research Symposium**, 12-13 October, 1988, Ft. Lee, VA; also **Ballistic Research Laboratory Memorandum Report BRL-MR-3755,** May 1989.

† It will be noted later that this notion can be applied as well to non-ballistic threats such as Directed Energy and Chemical Weapons analyses.

(here an aircraft), and the relevant kinematics as the two just begin to interact. The event may be signaled by the instant an unguided bullet begins to collide with a target or, as implied by the illustration, a fuze triggers an explosive mechanism in the vicinity of the target. The process of a LF test is to transform an undamaged target at **Level 1]** to a damaged target at **Level 2]**. The transformation process is the LF event itself, and is characterized by all the physical mechanisms of destruction. They may include main penetrators, fragments, blast, shock, fire, fumes and even synergistic effects. As a consequence of the LF transformation event, target damage may have occurred at **Level 2]**. We choose to think of **Level 2]** as characterized by a list of killed components; sometimes this is called a damage vector.

A target which has received damage may likely not continue to operate as before damage. In the case of a damaged aircraft illustrated here, parts of the control surfaces may be removed, hydraulic lines severed and electronic boxes impaired. In a test which might be performed, the rate-of-climb might be measured to see how this key performance property may have been reduced. The performance test is the transformation process which takes target damage at **Level 2]** and transforms it to reduced capability at **Level 3]**. The transformation from **Level 2]** to **Level 3]** can be thought of as characterized by engineering relations. It is important to note that the metrics of **Level 1]**, threat-target initial conditions, **Level 2]**, damaged components, and **Level 3]**, measures-of-capability are all measureable and objective metrics.

The capability state of **Level 3]** should be characterized by all capability measures which cause a military platform to have military utility or worth in a particular mission. For example, if the platform can move, the metrics might include measures of speed and agility. If the platform has a gun, the metrics might include time-to-acquire a target, rate-of-fire and hit dispersion.

The final transformation occurs as a platform with reduced measures-of-capability is exercised in a particular mission scenario. If the particular reduced measures-of-capability are unimportant to the mission at hand, then the utility of the platform may remain high. If not, the utility may be reduced, even drop to zero. The notion of measures-of-effectiveness or utility is illustrated as a **Level 4]** metric and would be reached through an operational test or war experience. Given the complexity of this transformation and the lack of real-world repeatability, we claim that **Level 4]** metrics are essentially not observable, but rather must be inferred through war games or developed *via* subjective processes.

One of the key insights provided by the V/L Taxonomy is that the discipline of vulnerability ranges over three distinct kinds of metrics, *damage*, *capability* and *utility*, and great care must be exercised to see that these metrics are not confused, incorrectly calculated or improperly applied.

In contrast to vulnerability, in which a threat interaction with a target is normally assumed, lethality often includes the process of getting the threat to the target. This is generally true in the assessment of direct-fire weapons such as tank-fired rounds. By contrast, studies of indirect-fire weapons, such as warheads delivered by artillery or rockets, generally begin with warhead initiation in the neighborhood of the target. Thus Fig. 1 includes a **Level 0]**, which represents the initial conditions for the launch of a direct-fired threat. The transformation of the threat at **Level 0]** to the arrival at the target (**Level 1]**) would occur here as the firing of the missile. In a set of repeated experiments, a distribution of threat arrival conditions could be generated. One particular condition at a time might be chosen to use for a given initial threat-target interaction at **Level 1]**.

3. V/L Taxonomy *via* a Mapping Abstraction

The V/L Taxonomy is useful in developing the mathematical abstractions needed for V/L modeling. Each of the levels of the process can be thought of as a mathematical space. As illustrated in Fig. 2, the cartoons in the middle of Fig. 1 describing the Levels have been replaced with ellipses representing these spaces.

The information at **Levels 0]** through **4]** can each be described by vectors within these spaces, here represented as bullets; however, the properties of the vectors are completely different from one space to the next. As mentioned above, the metrics of damage, capability and utility are not interchangeable.

As noted above, a LF test can be thought of as a mapping from **Level 1]** to **Level 2]**. If the LF shot were repeated it is likely that random physical processes could lead to a different damage vector; thus a different vector would result. LF tests and modeling efforts have shown[1] that the outcome for many LF tests can exceed 10^6 individual damage vectors. The high dimensionality of **Level 2]** space is at the core of the difficulty in validating V/L models.

The transformation processes listed at the right of Fig. 1 have been reproduced in Fig. 2 as well. It is useful to think of the transformations as mathematical operators. These operators operate on information on one level to yield information at the next. A nomenclature which has been adopted is to use a capital **O** (for operator), followed by subscripts indicating the input and output levels. Thus the $\mathbf{O}_{0,1}$ Operator represents the mapping of the threat from launch to the arrival at the target. The $\mathbf{O}_{1,2}$ Operator represents the the damage mapping process of a LF test. The $\mathbf{O}_{2,3}$ Operator represents the transformation to reduced capability of a target following damage. And the $\mathbf{O}_{3,4}$ Operator represents the transformation from reduced capability to military utility for a particular mission profile.

4. Granularity and the V/L Taxonomy

In addition to the delineation of the V/L Levels as discussed in **Section 1** and the nature of the mapping operators described in **Section 2**, the character and utility of a V/L code is further determined by the *granularity* reflected in its levels. For a particular level, granularity describes the extent to which a metric is amalgamated (*i.e.* integrated into larger elements) *vice* refined (*i.e.* subdivided into smaller elements). The former tendency is referred to as *lower* granularity while the latter is *higher* granularity.

This issue may be illustrated most easily by discussing its effect at **Level 1]**, where granularity relates directly to the resolution embodied in the target description.[2] Particularly in the early days of V/L analysis, target descriptions were not highly detailed. Only principal volumes of the target were modeled, major compartments and components, certainly not individual wires and hydraulic lines. One of many subjective areas of judgement that a V/L analyst invokes is a decision as to what level of detail to describe the geometry of the target.

Granularity is a part of **Level 2]** metrics as well. As damage is predicted, it is typically applied to the geometry explicitly described at **Level 1]**. For example, if a GPS (Gunner's Primary Sight) is modeled simply as a box at **Level 1]**, there are only very limited ways to predict damage at **Level 2]** to yield information about which circuit or optical element within the unit might now be dysfunctional. One such way might be via empirically derived distributions of the associated subcomponents or functionalities.

So too at **Level 3]**, the capability to fire a gun might be described simply as a Bernoulli trial (binary outcome) or, with greater detail (granularity), utilizing specific descriptors of gun rate-of-fire, time-to-acquire targets, hit dispersion, etc.

The issue isn't simply that each Level can have an arbitrary granularity, but that the granularity of a particular level *requires* a minimum granularity at the prior level. Using the previous example, the high-resolution description of gun performance at **Level 3]** can not be performed without the support of a sufficiently detailed damage vector at **Level 2]**. And the adequacy of the damage vector at **Level 2]** is in turn enabled by the detail of the geometry at **Level 1]**.

The configuration of a V/L model in terms of the granularity invoked must be based on the set of desired metrics which it is to support. The desired metrics may typically be distributed over a number of levels, and a sufficiency check must be made to ensure that the resolution required at a given level is adequately supported at each prior level.

5. Insights Provided by the V/L Taxonomy.

There are a number of important aspects of the taxonomy, particularly for understanding the definitions for vulnerability, lethality and survivability.

- The V/L metrics associated with each of the **Levels 0]** through **4]** are fundamentally different, one from another. That is to say, component damage across a weapon platform is different from (potentially diminished) capability of the platform is different from the (possible reduction in) military utility of the platform. Both vulnerability of a platform or the lethality of a weapon can be *defined* in any combination of metrics from **Levels 2]**, **3]**, and/or **4]**.
- The five levels are sequential, orthogonal and non-permutable.
- Modern V/L modeling schemes must track the taxonomy so that **Level 2]** and **3]** metrics can be compared with the results of field tests.

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2. Paul H. Deitz and Keith A. Applin, *Practices and Standards in the Construction of BRL-CAD Target Descriptions*, **Army Research Laboratory Memorandum Report ARL-MR-103**, September 1993.

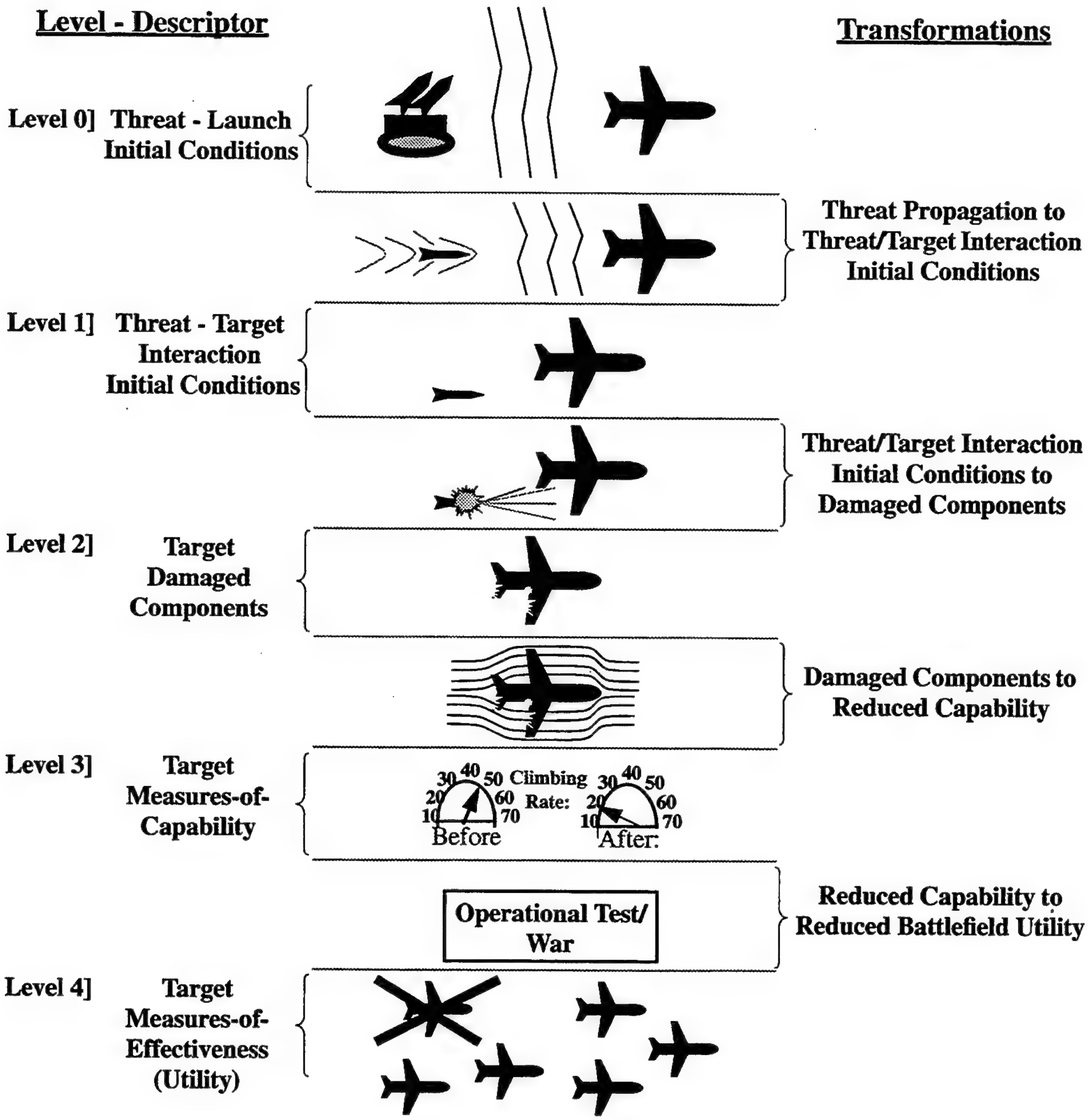

Fig. 1. V/L Taxonomy illustrated with physical and engineering processes in the center column. The Levels 0] through 4] are described on the left. The transformation processes between the Levels are described on the right.

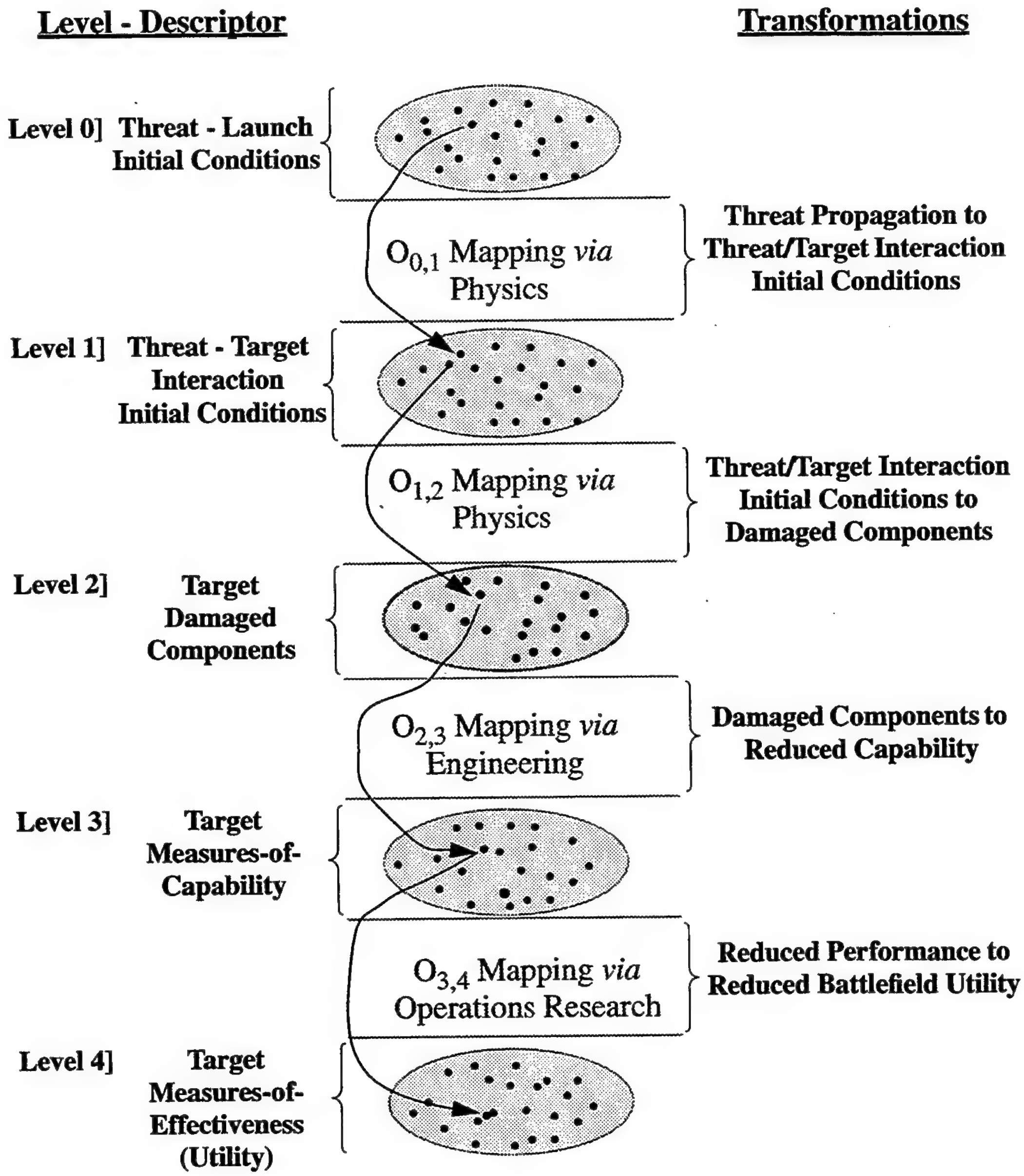

Fig. 2. V/L Taxonomy illustrated *via* a Mapping Abstraction. The ellipses in the middle column represent mathematical spaces. The points contained within represent vectors. The arrows represent mapping operators which take a vector at one level and perform a mapping to the next lower level.

- The operators are generally stochastic and non-linear; therefore the transformations are not invertible, and multiple levels (*e.g.* **Level 2]** to **4]**) cannot be properly mapped in a single process.
- In certain V/L modeling tasks, the mathematical mapping operators must utilize stochastic processes to yield accurate results. This is most notably true in the damage operator, $\mathbf{O}_{1,2}$, where expected-value transformations lead to incorrect results.
- The effect of target damage, whether simultaneous (*e.g.* the striking of two or more artillery fragments), time-ordered (*e.g.* a volley of impinging rounds), or caused by multiple physical mechanisms (*e.g.* blast and/or shock and/or fire) must be aggregated at **Level 2]**, the damage vector level. Clearly if, for example, a personnel carrier were struck by two artillery fragments which each happened to kill the same component(s), then the damage at **Level 2]** from both fragments would be no greater than the damage from either fragment individually. However the standard method for computing artillery effectiveness for the past 30 years has been to compute an approximation of a damage vector (**Level 2]** metric) for each fragment, map the resulting damage directly to a Loss-of-Function (**Level 4]** metric), and then to combine each of the system LoFs (using a formula resembling the survivor rule for combining probabilities) to get an overall vehicle LoF. The merging of individual damage mechanisms at **Level 4]** rather than at **Level 2]** is a major difficulty in a substantial amount of today's battlefield simulations. A corollary to this observation is that whenever a battlefield threat is played against a particular target, that target should not be assumed to be pristine, but reflect all prior aggregated damage except that which may have been repaired.
- **Level 4]** metrics, essentially battlefield utilities, cannot be observed through testing. In addition, to get to **Level 4]** *via* the $\mathbf{O}_{3,4}$ mapping operator requires the incorporation of tactics, doctrine, threat systems and battlefield environment; this division of labor is clearly in the province of the force-on-force modeler, not the vulnerability analyst.
- Each level of the taxonomy as it is applied in a given V/L model reflects a certain level of granularity (or resolution). The ability to perform adequately a computation at one level in the taxonomy requires a particular minimum level of granularity at the preceding level. The granularities of a V/L model metrics are critically related to the applicability of that model to a particular analysis purpose.

6. Applications of the V/L Taxonomy

Since the original notion of the V/L Taxonomy was generated, many extensions have been made. Delineations of what belong at the levels *vice* what constitute operators, the role of the process structure in V/L model accuracy and the properties of operators have been made clear.[3-6] The V/L Taxonomy has been used to propose Live-Fire Test strategies[7] which, to the maximum extent known, yield predictive metrics compatible with field observables and are also amenable to statistical validation procedures. It has been applied to the description of personnel vulnerability[8] and the description of **R**eliability, **A**vailability and **M**aintainability (**RAM**).[9] It is used across ARL/SLAD for couching metrics and transformation operators in clear and unambiguous ways, not just for ballistic threats, but for Electronic Warfare and Chemical Threats [10] as well.

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3. Michael W. Starks, *Assessing the Accuracy of Vulnerability Models by Comparison to Vulnerability Experiments,* **Ballistic Research Laboratory Technical Report BRL-TR-3018,** July 1989.
4. Paul H. Deitz, Jill H. Smith and John H. Suckling, *Comparisons of Field Tests with Simulations: Abrams Program Lessons Learned,* **Proceedings of the XXVIII Annual Meeting of the Army Operations Research Symposium,** 11-12 October, 1989, Ft. Lee, VA, pp. 108-128; also **Ballistic Research Laboratory Memorandum Report BRL-MR-3814,** March 1990.
5. J. Terrence Klopcic, Michael W. Starks, James N. Walbert, *A Taxonomy for the Vulnerability/Lethality Analysis Process,* **Ballistic Research Laboratory Memorandum Report BRL-MR-3972,** May 1992.
6. James N. Walbert, Lisa K. Roach and Mark D. Burdeshaw, *Current Directions in the Vulnerability/Lethality Process Structure,* **Army Research Laboratory Technical Report ARL-TR-296,** October 1993.
7. Paul H. Deitz, Michael W. Starks, Jill H. Smith and Aivars Ozolins, *Current Simulation Methods in Military Systems Vulnerability Assessment,* **Proceedings of the XXIX Annual Meeting of the Army Operations Research Symposium,** held 10-11 October 1990, Ft. Lee, VA; also **Ballistic Research Laboratory Memorandum Report BRL-MR-3880,** November 1990.
8. Michael W. Starks, *Improved Metrics for Personnel Vulnerability Analysis,* **Ballistic Research Laboratory Memorandum Report BRL-MR-3908,** May 1991.
9. Lisa K. Roach, *Fault Tree Analysis and Extensions of the V/L Process Structure,* **Army Research Laboratory Technical Report ARL-TR-149,** June 1993.
10. William J. Hughes, *A Taxonomy for the Combined Arms Threat,* **Chemical Biological/Smoke Modeling & Simulation (M&S) Newsletter, Vol. 1, No. 3,** Fall 1995.

7. V/L Taxonomy and Survivability

A number of times we have emphasized the importance of not confounding the different kinds of V/L metrics associated with **Levels 2], 3]** and **4]**. The data associated with a **Level 2]** metric is straightforward— it is simply an accounting of damaged or killed components. At **Level 3]**, the metrics are capability. Capability measures can be defined clearly in terms of measureables such as top speed, minimum speed, rate of acceleration, rate of fire, etc. **Level 4]** metrics may best be thought of as *utilities* and therefore are dimensionless. It may be helpful to review a hypothetical example of an aircraft performing a military mission. With a view to Fig. 1, let us assume that a missile attack has led to severing a fuel line to one of two engines on the aircraft. The damage vector at **Level 2]** is damage vector of one element, one killed fuel line. Applying the capability operator $\mathbf{O}_{2,3}$ to the damage vector gives the following result at **Level 3]**; the aircraft is able to fly straight and level, but not climb. Now we examine the Military Utility Operator, $\mathbf{O}_{3,4}$. To apply this operator, a number of missions must be defined. In one mission, it might be necessary to climb rapidly to avoid ground ordnance. In mission two, it might only be necessary to maintain level flight. Thus we could define two $\mathbf{O}_{3,4}$ mapping operators. In the case of the first, the damaged aircraft could not fulfill the mission and would have a utility of zero. In the case of the second mission, the mission could be supported, giving a utility of one. One can envision missions which when applied against partially performing platforms would result in partial utility $[0.0 < U < 1.0]$. Given some set of mission utilities, it is then possible to develop an expected utility, averaged over some set of missions.

Often utilities, averaged or otherwise, are used by the community of war gamers. The utilities are often simply *defined* to be probabilities of a certain class of kill. The utility, on the same interval as a probability, is used in the war game to make a draw, assuming a ballistic encounter. Based on the outcome, the platform may be removed from the conflict. Potentially three errors are committed by this practice.

1] Binning a vulnerability metric in a war game scenario which has already been binned by a vulnerability analyst: The war gamer should take the capability information from **Level 3]** and play that characterization of the platform in his mission encounter. The war game will then *define* the utility of the (damaged) platform.

2] Averaging two or more utilities: Often averages are performed over the outcomes of multiple binning processes. This is legitimate mathematically. However a major problem occurs when an average utility is applied to a specific mission. They may in fact be very different numbers leading to highly inaccurate conclusions.

3] Turning a utility into a probability: A practice which has seen widespread use in the ground arena has been to argue that an average battlefield utility is equivalent to the probability of total loss of the modeled capability.

This third practice has been shown wanting for many years,[11,12] but the numbers provided by the V/L community to its customers are still referred to as "probabilities of kill" or "expected loss-of-function", even if at their foundation, they may suffer from some or all of these three serious problems.

Finally, if a series of utilities is derived as a function of ballistic threats introduced at **Level 1]** and played against a number of missions in the $\mathbf{O}_{3,4}$ utility mapping, it would appear that we have proper measures for what might be called *ballistic survivability*. We have ignored all other factors in survivability including the probability of detection at various wavelengths, agility, etc. One can think of *overall survivability* as the combined output of an $\mathbf{O}_{3,4}$ utility map utilizing not only the **Level 3]** capability metrics of ballistic measures, but using the similar capability metrics from all of the other disciplines which affect survivability.

11. James R. Rapp, *An Investigation of Alternative Methods for Estimating Armored Vehicle Vulnerability*, **Ballistic Research Laboratory Memorandum Report ARBRL-MR-03290**, July 1983.

12. Michael W. Starks, *New Foundations for Tank Vulnerability Analysis (With 1991 Appendix)*, **Ballistic Research Laboratory Memorandum Report BRL-MR-3915**, May 1991.

In the Army, there is now movement to repair these logical lapses. Recent work with battlefield modelers[†,‡] has shown that a war game is the singular place where battlefield utility should be estimated, and this in a robust situation where tactics, doctrine and appropriate stochasticism can be properly played. Thus the **Level 3]** to **4]** mapping for vulnerability/lethality must be played along with all of the other relevant platform metrics outside of the pure V/L milieu.

Appendix A

Definitions of Lethality, Vulnerability and Survivability[□]

Vulnerability

The characteristics of a system that cause it to suffer a degradation [loss or reduction of capability to perform the designated mission(s)] as a result of having been subjected to a hostile environment on the battlefield. It is generally an assumption in vulnerability studies that the threat warhead has engaged the target.

Lethality

The ability of a system to cause the loss of, or a degradation in, the ability of a target system to complete its designated mission(s). Often for direct-fire weapons, the delivery of the warhead from launch to target impact is integral to the lethality analysis. For indirect-fire weapons, studies often begin with warhead initiation in the neighborhood of the target.

Survivability

The capability of a system (resulting from the synergism among personnel, materiel, design, tactics and doctrine) to avoid, withstand or recover in hostile (man-made and natural) environments without suffering an abortive impairment of its ability to accomplish its designated mission. If the two facets under control of a weapons designer, materiel and design, are lumped into *System Characteristics*, and the effects of personnel are distributed appropriately over the three remaining variables of *Characteristics*, *Tactics* and *Doctrine*, then Survivability can be written functionally as:

$$\begin{aligned}\text{Survivability} = f\ [&\text{Threat (Characteristics, Tactics, Doctrine)},\\ &\qquad\text{Battlefield Environment},\\ &\qquad\qquad\text{System (Characteristics, Tactics, Doctrine)}]\end{aligned}$$

† Private communication with personnel at TRAC/WSMR. War Gamers at TRAC are modifying a version of CASTFOREM so as to accommodate ballistic inputs at **Levels 2]** and **3]**. These war games, as a consequence of their outputs, provide a **Level 3]** to **Level 4]** mapping (*i.e.* utility weighting).

‡ Private communication with W. J. Brooks, Jr., of AMSAA. A DMSO-funded ATTD Program directed by Mr. Brooks is being configured so as to accept **Level 2]** (disabled components) and **Level 3]** (degraded capability) metrics from V/L models.

□ Consistent with *Defense Acquisition Management Policies and Procedures*, **DoD Instruction 5000.2,** February, 1991.

MODELING BALLISTIC LIVE-FIRE EVENTS

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Paper presented at the 7th Annual TARDEC Symposium, held at the Naval Postgraduate School, Monterey, CA, March 26-28, 1996.

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MODELING BALLISTIC LIVE-FIRE EVENTS

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ABSTRACT

This paper explains the need for a stochastic vulnerability model to support the analysis of live-fire testing. The history of the development and use of such a model over the last decade is summarized by demonstrating the need for new methodologies and the establishment of the SQuASH vulnerability model. A brief review is made of the various assessment efforts made to compare SQuASH model outputs with various Abrams Live-Fire Test results. This has lead to a model improvement plan for upgrading SQuASH. The incorporation of the upgraded model into the MUVES suite of vulnerability codes and its application to the upcoming Armored Gun System (AGS) Live-Fire program are described.

INTRODUCTION

Nearly a decade ago, the U.S. began a new form of vulnerability experimentation called Live-Fire Testing (LFT) (ref. 1). In LFT, a complete vehicle, such as a tank or armored personnel carrier, is placed in full battle readiness, engine running, full load of fuel and ammunition, and fired at with an overmatching threat. Only the absence of a live crew compromises actual encounter realism. Congressional legislation had been passed recognizing that in spite of design limits defining absolute protection, systems should nevertheless be tested according to threats expected to be encountered. Many such threats could be overmatching. The issue was to mitigate and ameliorate such events. In addition, LFT can uncover vulnerabilities not foreseen by vehicle designers and improve survivability.

The first LFTs occurred against the M113 armored personnel carrier.[†] For the most part, these results were non-controversial. By 1985, testing had begun on the more modern Bradley fighting vehicle. To accompany field testing, the program test plans required that vulnerability models be used both to predict and, subsequently, to be upgraded by actual LFT results. As the test proceeded and the results were compared to model predictions, an apparent pattern of disagreement began to emerge. Critics in the Office of the Secretary of Defense (OSD) questioned the fidelity of existing ballistic vulnerability modeling. As the Vulnerability/Lethality Division (VLD) of the former U.S. Army Ballistic Research Laboratory (BRL)[‡] headed into the Abrams Live-Fire program, a goal was set to develop a new model — one designed to simulate actual live-fire events, including the statistical variations commonly encountered.

DEVELOPMENT OF THE SQuASH MODEL

The SQuASH model was developed specifically for the purpose of providing a tool for predicting and understanding live-fire events. No existing model was adequate for this purpose; either they did not predict outcomes that could actually be measured in the field or they did not account for the variability of live-fire outcomes — or they were deficient in both of these areas.

Model Requirements to Address Live-Fire Testing

When the need for vulnerability modeling to support LFT arose in 1985, a number of insights began to emerge:

† Bradley live-fire actually began before the M113 tests, but the M113 firings were completed first.

‡ On 30 September 1992, the U.S. Army Ballistic Research Laboratory (BRL) was deactivated and subsequently became part of the U.S. Army Research Laboratory (ARL) on 1 Ocotober 1992.

observable damage or vehicle capability. Vulnerability models have historically done a poor job of developing metrics that are observable in the field. The emphasis in vulnerability modeling today is on:

— Direct battle damage (i.e., "killed" or nonfunctioning components) and

— Platform capability (the relationship between "killed" components and measurable platform function, rate of gun fire, top speed, etc.).

Battlefield utility, which is not an observable, is now seen to be the proper province of the force-on-force modeler.

- Few vulnerability models reflected the variability that is intrinsic to many ballistic interactions. When penetrators strike a target and perforate the skin, the armor spalls into numerous fragments of varying mass, velocity, shape, and orientation. However, the existing models all converged on a single, expected-value for the final result, rather than yielding statistical distributions of possible outcomes. Some models attempted to calculate the probability of damaging components individually along a particular shotline but said nothing about the probability of damaging components in combination with one another.

In addition to establishing the need for a new model, this retrospection of existing vulnerability models also made it clear that:

- There is a dearth of information concerning many of the mechanisms of physical damage from ballistic interactions.
- There are many ballistic mechanisms, which can cause significant damage, that were not modeled at all. These typically included blast, shock, fire, and toxic fumes.

Another important by-product of this reexamination has been the establishment of a formal framework within which to understand and categorize the elements and properties of vulnerability/lethality (V/L). Termed the *V/L Taxonomy* (ref. 2), it provides a method to decompose the elements of V/L into a sequence of simpler constituent parts called *levels*. The levels relate to each other in a specific processing order and are fundamentally different. Each has its unique and appropriate use in the general scheme of V/L assessment and are related to each other by mapping operators. It can be seen that most (if not all) of these mapping operators must be stochastic in order to support the variability so intrinsic to many of the V/L processes. A further characterizing property of the vulnerability levels is the degree to which specific metrics are aggregated (i.e., lumped together) *versus* refined (i.e., subdivided into smaller elements). The word *granularity* is used to describe this property. Since the earliest notions of the V/L Taxonomy were first expressed (ref. 2), much progress has been made to formalize and extend this concept. The concept of the V/L Taxonomy has applicability ranging from how platform component damage relates to platform performance to how platform metrics should feed force-on-force models. (The reader is referred to ref. 2 for a current summary of this framework and its ramifications.)

Need for a Stochastic Model

To address the shortcomings described previously, in 1985 the V/L Division (VLD) of BRL embarked on a significant initiative to establish a new kind of vulnerability code, which would explicitly embody *observable model metrics supported by stochastic methods*. The new code, called *SQuASH* (*S*tochastic *Qu*antitative *A*nalysis of *S*ystem *H*ierarchies), was applied to some 48 Abrams shots performed in the 1986 time frame. SQuASH supported the following four sources of variability, subject to random sampling:

- Weapon Hit Point — sampled in the neighborhood of the intended impact point.
- Warhead Performance — from a Gaussian distribution with mean and standard deviation obtained from experimental data.
- Residual Penetrator Deflection — from a Gaussian distribution with mean and standard deviation obtained from the variability of experimental data, width of the spall cone, and a Poisson distribution that controls the number of spall fragments. The parameters for these distributions were derived from experimental data.
- Component Pk Characterization — from a Poisson distribution to determine the number of impacts on a component and a uniform distribution to perform a Bernoulli trial on whether the component was "killed" or "not-killed."

Because of the paucity of knowledge for many sources of damage, as well as insufficient time to code new algorithms, the only damage mechanisms modeled for this analysis were main penetrator (including residual penetrator) and behind-armor debris spall.

and behind-armor debris spall.

ASSESSMENT OF SQuASH — LESSONS LEARNED

Following the Abrams program, a number of significant efforts were made to compare the model results with the field observables. This effort proved daunting as the SQuASH model exercise indicated the possibility of more than 10^6 individual combinations of component "kill" records for particular warhead-target encounters. A thousand, or even ten thousand, Monte Carlo replications with the model may not be sufficient to produce the exact sequence of damaged components observed in the field. Validation of a stochastic vulnerability model was — and still remains — problematical.

Early Assessment of SQuASH

The initial published results addressing model validation for Abrams (refs. 3-5) live-fire shots resulted in the following conclusions (taken from ref. 5):

- Tests on the probability of armor perforation were in good agreement with model predictions.
- Tests on the probability of catastrophic "kill" were also in good agreement with model predictions.
- Tests on the Mobility "Kill" prediction were at the 85% agreement level with model predictions.
- Tests on the Fire Power "Kill" prediction were at the 33% level of agreement with model predictions.

A number of other issues came to the fore. It was clear that fire, secondary spall, ricochet, and blast sometimes played dominant roles. The absence of algorithms in the model to describe these potential sources of damage needed to be redressed. In addition, unless there were major disagreements between the model and the field tests, the very complexity of ballistic interactions — with the concomitant space of greater than 10^6 discrete outcomes to be compared with a small number of single test results — made statistical inference problematic.

In the time since 1986, various upgrades to SQuASH have been made and the model has been used in a number of Army Live-Fire programs. These include M1A1, Paladin, M1A2, and T-72. To avoid confusion, note that the initial configuration of SQuASH used for the Abrams M1A1 live-fire program was written in FORTRAN. The version of SQuASH that is being incorporated into MUVES (described in subsequent sections) is written in the C language.

Independent Assessment of SQuASH

In addition to the previous in-house comparison, VLD also contracted with The SURVICE Engineering Company in 1991 to perform an independent assessment of SQuASH. Their findings will be discussed shortly.

Meanwhile, in 1993 the Army was involved in the Abrams M1A2 upgrade. To decrease the cost of testing, the Department of the Army (DA) proposed to substitute SQuASH predictions for a portion of LFT. To estimate the risk associated with this strategy, OSD tasked the Institute for Defense Analyses (IDA) to perform an independent assessment of SQuASH. In a set of charts,[†] IDA appears to have utilized a novel strategy in which the probabilities of damaging particular components using *multiple* threats at *various* hit locations are aggregated over many tests. Via this strategy, the paucity of field tests matching each model exercise would appear to have been somewhat mitigated. Based on these findings, IDA drew the following three conclusions:

- SQuASH is a poor predictor of damage at the component level.
- The number of components where the damage was unexpected ($P_k \leq .05$) is comparable to or exceeds the number where the damage was *expected.*
- A large fraction of the damaged components was never reported by the model.

Of the 259 "killed" components used in the IDA study, SQuASH correctly predicted damage to 49% (127) and incorrectly predicted no damage to 51% (132). The latter category can be further subdivided into two groups:

1. Component was hit but not predicted to be damaged — accounting for 21% (54 components) and
2. Component was not hit by a ray — accounting for 30% (78 components).

IDA did not provide insight into the possible origins of SQuASH-Abrams LFT discrepancies. From our analyses, these two categories correspond to separate issues and are being addressed by different strategies. The first category illustrates a deficiency of modeling the vulnerability of critical components. Past modeling used an average

† To date, no formal report of the findings has been published by IDA.

probability of kill (P_k), averaged over hit location and direction of penetration. Due to the inherent variability of component vulnerability, a distribution of possible outcomes rather than a single expected value may be more appropriate — and we are exploring this option. However, another factor that may contribute to the discrepancy — and may even be more important — is the use of a *single* draw on the component P_k to produce a binary kill/no-kill outcome. Even if the component is modeled extremely well, the expected number of Bernoulli trials required to realize a "kill" is $1/P_k$, where P_k is the component's probability of "kill." Thus an unintended result of the Bernoulli trial approach is to effectively under-sample the components having low P_k values. We now believe that a better approach may be to use the *actual P_k value in the Criticality Analysis* (see ref. 6, for an example of the latter) — and the methodology is being changed to accomplish this.

The second category illustrates a geometric sampling problem: If SQuASH never samples a component, it can never be regarded as damaged. The methodology being developed in the new SQuASH model will be using a different approach altogether for generating spall fragments (see *Improvements to SQuASH* below), as well as modern recursive techniques to produce secondary burst points.

In general, the conclusions of the SURVICE study (ref. 7) were not substantially different from the IDA study, although they do contain more detail. However, the SURVICE study used a more stringent statistical test called the *Modified Ordering of Probabilities* Test (ref. 8).

MUVES — NEW CONTEXT FOR SQuASH

In 1986, concurrent with the development of SQuASH, the VLD initiated a project to develop a computer architecture, written in the C language, that would be modular in nature, strongly coupled to the UNIX operating system, and would minimize vulnerability code redundancy. This effort resulted in a computer environment called *MUVES* (*M*odular *U*NIX-based *V*ulnerability *E*stimation *S*uite) (ref. 9). The development was made possible by a number of new insights, including:

- The actual vulnerability process can be broken into specific building elements. These elements can calculate possible damage in uniform ways regardless of the threat-material class, can aggregate damage in consistent ways to estimate component "kill," and can map component "kill" to platform capability in the same general fashion.
- Each vulnerability code is composed principally of support modules that are not threat-target specific. Eighty-five percent of the code includes modules, for example, to manage memory, interrogate geometry, interpolate tables, and draw random numbers. All of these modules should be applicable to many classes of vulnerability computation for many threats and many targets.
- The computer methods and techniques historically used to code vulnerability models are inadequate to the task of rapid upgrade, code VV&A, extensibility to new encounter conditions, and ability to share code among various threat-target classes.

Over the past six years, the Ballistic Vulnerability/Lethality Division (BVLD) has been moving its vulnerability codes under this single, consistent MUVES environment. The first code integrated into MUVES was the direct-fire, lumped-parameter, Compartment Model, historically called VAMP (ref. 10). The resulting code has supported many direct-fire studies over the past years. In the summer of 1995, an aircraft-missile model called *MAVEN* (*M*odular *A*ir-system *V*ulnerability *E*stimation *N*etwork) (ref. 11) was placed in production. The first operational capability embodied armor-piercing (AP) threats against aircraft and was used for live-fire predictions in the current Apache-Longbow program (ref. 12). Now in final beta testing is an indirect-fire model called *SAFE* (*S*tatistical *A*nalysis of *F*ragment *E*ffects) (ref. 13). A major improvement for indirect-fire weapons, including artillery munitions, SAFE can assess multiple burst points, proper target perspective, random fragments (including mass, velocity, shape, and orientation), and aggregate damage correctly at the vehicle component level. SQuASH is also moving to the MUVES environment. Not only is the overhead in dealing with the SQuASH FORTRAN environment too high, it is incapable of supporting the proper inclusion of new damage mechanisms.

SQuASH IMPROVEMENTS AND APPLICATIONS

Methodology Improvements

With the intent of redressing the modeling deficiencies that were identified previously (see *ASSESSMENT OF SQuASH — LESSONS LEARNED*), the following changes to the methodology are being implemented:

- **Upgraded Kinetic Energy (KE) Long Rod Armor Penetration:** Based on the research of Alekseevskii (ref. 14) and Tate (ref. 15), this methodology applies to a wide variety of threat-target interactions by accounting for hydrodynamic flow of both target and penetrator that can arise in the hypervelocity regime. This methodology also makes explicit use of physical quantities, such as Brinell hardness, that can be varied in a stochastic manner when it is appropriate to do so — such as when the penetrator is close to the ballistic limit v_{50} of perforation.
- **New Spall Characterization:** A substantial effort has been expended to improve (ref. 16) the SQuASH spall model. The upper section of Fig. 1 shows a flash radiograph of a shaped-charge jet following armor penetration. An elliptical debris cloud is evident. The lower section shows the geometric characterization of the shell shape and velocity field used to model this phenomenon.

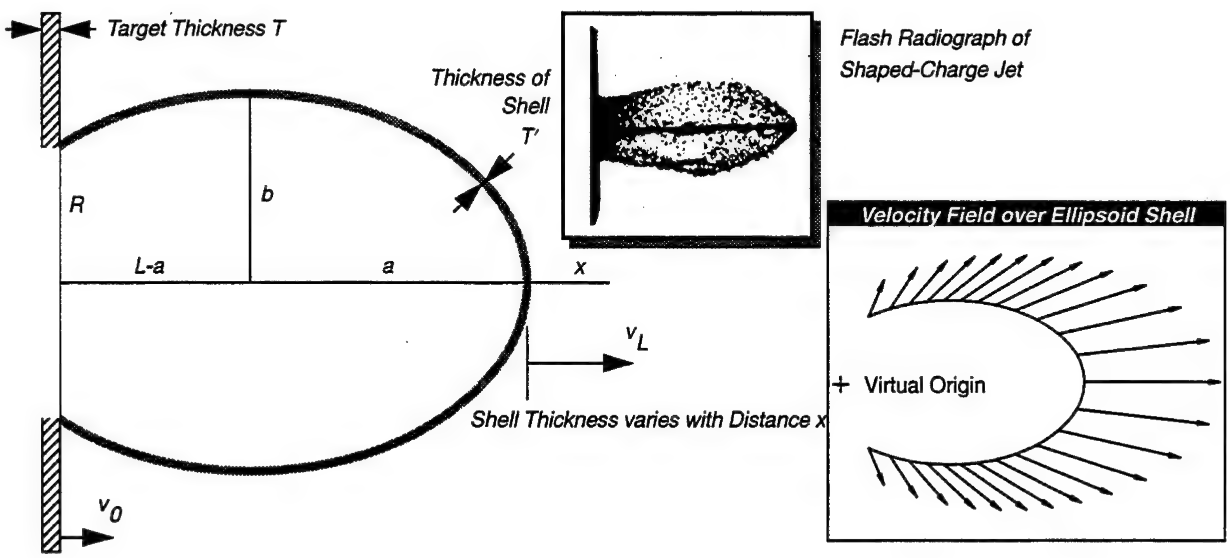

Figure 1. *Behind-Armor Debris Characterization*

The image on the left in Figure 2 shows a three-dimensional rendering of a spall cloud computed with expected-value parameters for each surface element on the cloud topology. The image on the right in this

figure shows the same plot with stochastic spall generation enabled.

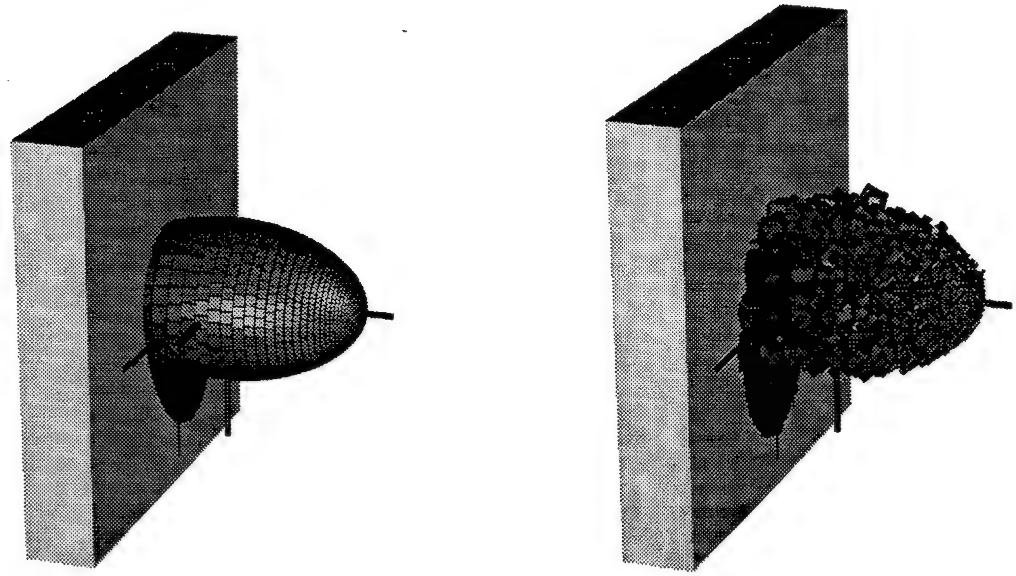

Figure 2. *Three-Dimensional Renderings of Spall Cloud (Images provided by Gary Moss)*

- **Multiple Barrier Penetration:** The code will propagate the threat (spall or penetrator) until it comes to rest or exits the vehicle. The FORTRAN version of SQuASH did not track spall beyond the first barrier, and broken penetrator pieces were not tracked beyond the sixth barrier.
- **Accounting for Ricochet:** Ricochet was not accounted for in the FORTRAN version of SQuASH, although the LFT assessors noted the occurrence of ricochet in the live-fire tests. SQuASH will be using a ricochet criterion published by Tate (ref. 17) that is based upon penetrator velocity and target obliquity. When the ricochet criterion is satisfied, the code will go on to compute the ricochet angle and residual velocity (ref. 18).
- **Upgraded Personnel Incapacitation:** The FORTRAN version of SQuASH used the Kokinakis-Sperrazza criteria for crew incapacitation (ref. 19). The MUVES version of SQuASH will use "Ballistic Dose" (ref. 20). This is a combination of mass, velocity, and number of fragment hits that was formulated from extensive runs of the *ComputerMan model* (ref. 21). It removes a number of limitations of the older methodology.
- **New Component Characterization:** The FORTRAN version of SQuASH performed a Bernoulli trial on each component that was hit to get a binary "kill/no-kill" outcome. Since the P_k of the component will be known as a function of the encounter conditions, the MUVES version of SQuASH will output the P_k value itself. This value will then be passed along from each component and combined using fault-tree algebra. This change in methodology should go a long way toward alleviating the sampling problem that has been identified in the IDA and SURVICE studies.
- **New Sampling Procedures:** The FORTRAN version of SQuASH used the expected number of fragments along a trajectory, whereas the MUVES version of SQuASH brings more fidelity to the process by specifically generating a ray for each fragment. This allows for more realism and a more natural application of stochasticism. The MUVES version of SQuASH will have a library of 20 continuous distributions and 7 discrete distributions to simulate various random processes. Furthermore, this library is extensible so that the user can use an empirical distribution or a user-specified function to represent a given stochastic process. Among the stochastic processes that the MUVES version of SQuASH will consider as the model is fine-tuned are:

- Hit Location
- Penetration Depth (based upon variation of material properties)
- Ballistic Limit Velocity (based upon spread about the v_{50} value)
- Penetrator Breakup (based on velocity, obliquity, and yaw)
- Deflection of KE Long Rod Penetrators
- Ricochet Angle of KE Long Rod Penetrators
- Spall (fragment velocity, size, direction, and orientation)
- Component P_k

We note again that neither the SURVICE nor IDA study was able to determine specific causes for disagreement between SQuASH and the Abrams LFT program. Our diagnosis of the disagreement is based upon past experience, knowledge of the modeling methodology, and insight. As a result, we believe that the planned improvements outlined in this section are plausible cures for these deficiencies but, of course, it will be the actual application of the model to Live-Fire that will determine our degree of success.

Application to the Armored Gun System (AGS)

The first application for the MUVES version of SQuASH comes soon with the AGS program. Figure 3 shows a shaded rendering of the BVLD-generated image. This image was generated with the BRL-CAD™ suite of supporting utilities.

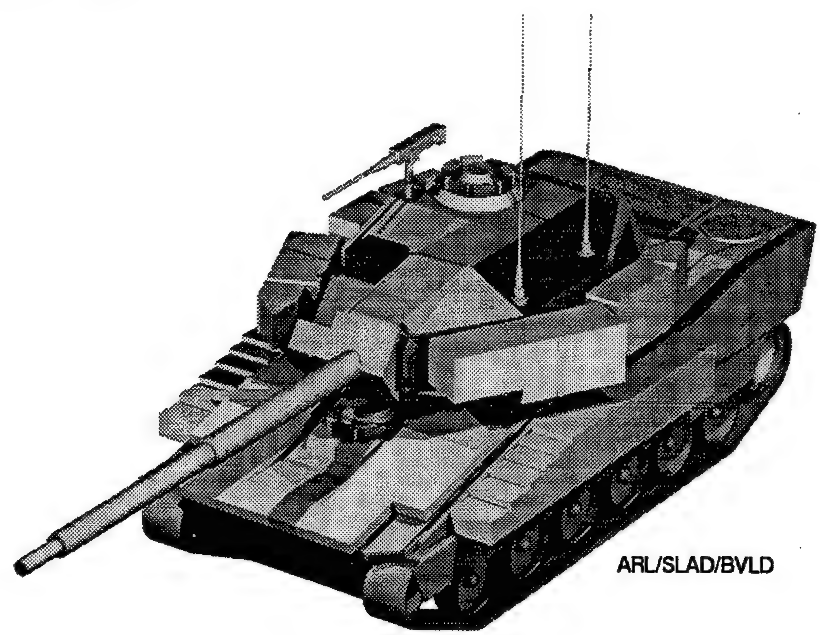

Figure 3. *A shaded rendering of the Armored Gun System (AGS) (Image provided by Ted Muehl)*

AGS will constitute the Army's new combat vehicle, but in the form of a highly deployable, light-weight vehicle, with high fire-power and reconfigurable armor protection. Analysts are assembling the various required inputs including target description, fault-trees, penetration-fragment parameters and component P_k functions. This preparation phase is particularly challenging due to 1) the multiple armors being used on the AGS and 2) the paucity of relevant ballistic databases, at least in comparison to that known at a comparable time in the Abrams program.

The MUVES environment is being upgraded with the software improvements previously discussed (see *IMPROVEMENTS TO SQuASH*). The application of the new MUVES version of SQuASH to the AGS will provide valuable information on the improvement strategy that we have outlined in this report.

Future Improvements

In addition, studies continue elsewhere in ARL to bring insight into the ballistic phenomena of shock-blast loading and resulting component damage. As these complex damage mechanisms are gradually understood and modeled, BVLD will integrate appropriate algorithms into the MUVES environment. This strategy has already resulted in great leveraging. First, mechanisms are easier to model and integrate into MUVES because the support structure already exists. Second, when a new mechanism is included one place in the MUVES environment, it is available for all other approximation methods sharing this environment. As the MUVES environment matures and these methods gain sophistication, we expect a gradual shift away from the long-existent problems of code implementation and towards the fidelity and calibration of specific ballistic phenomena and related platform dysfunction.

NEED FOR STATISTICS

A recurring theme throughout the application of SQuASH to LFT has been the need for statistical measures of comparison (see refs. 8, 22-24). Even the question of what test to use is not at all obvious. Different analysts apply different tests to judge the comparison between model predictions and field test results. Furthermore, there are various levels at which the comparison can be performed — ranging from component damage states to platform performance. Nor is this problem likely to be solved any time soon; it is an active, ongoing area of research.† Even if we did not have the SQuASH model, we would still be faced with the problem of drawing statistically significant conclusions from a small number of live-fire tests, each of which is one realization from a different underlying distribution of possible outcomes. Of course the problem of inferring statistically significant conclusions from model predictions *vis-a-vis* live-fire tests extends beyond SQuASH to virtually all of the high-resolution V/L models whether within or without the MUVES environment.

CONCLUSIONS

In this paper, we have reviewed a decade of Live-Fire V/L testing and modeling. The test programs have spurred substantial improvements to the extant suite of V/L codes, one of which is the SQuASH model. Comparisons of SQuASH model predictions with field tests indicate that fragment damage is underpredicted; other damage mechanisms must be added. A detailed strategy for code upgrade has been outlined including not just specific computational fixes, but the use of a general V/L computing environment called MUVES. Currently SQuASH is being upgraded in preparation for the AGS live-fire program. The next half year will provide a set of new opportunities to gauge progress in V/L model improvement.

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† For example, an ARO/Academia/ARL Workshop was held 11-12 September 1995 at ARL/SLAD. Under the sponsorship of Dr. Jagdish Chandra, Director of the Army Research Office Division of Mathematics and Computer Science, a group of academic experts met to discuss various computer science and statistical issues in the area of vulnerability/lethality.

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DEVELOPMENTS IN MODELING BALLISTIC LIVE-FIRE EVENTS

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DEVELOPMENTS IN MODELING BALLISTIC LIVE-FIRE EVENTS

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This paper presents our plan for Verification, Validation, and Accreditation (VV&A) of the Stochastic Quantitative Analysis of System Hierarchies (SQuASH) Model. This model was developed for the express purpose of providing a tool to the vulnerability/lethality (V/L) analyst to use for planning, analyzing, and assessing Live-Fire Test shots of Armored Fighting Vehicles (AFVs). From its initial conception, it was designed to use a *high-resolution* target description of an AFV and to be *stochastic* in nature — two essential characteristics, we would argue, to be able to meet its intended purpose. Modeling and simulation (M&S) are very valuable tools for understanding V/L issues in a well-balanced, cost-effective program of analysis and testing. However, before SQuASH can be treated as a credible supplement to Live-Fire Testing (LFT), it must first undergo a comprehensive verification and validation process. This paper presents our plan to accomplish this goal.

INTRODUCTION

Over a decade ago, Congress mandated [Live Fire Testing, 1987] that new Armored Fighting Vehicles (AFVs) must undergo Live-Fire Testing (LFT) before they are fielded. The AFV is placed in full battle readiness, with engine running and a full load of fuel and live ammunition, and subjected to firings from an overmatching threat munition. Only the use of manikins for a live crew compromises the realism of an actual battlefield encounter.

As we took inventory of the state of vulnerability models in 1985, it became clear that existing models were not adequate for predicting live-fire events:

- Few vulnerability models reflected the variability that is intrinsic to many ballistic interactions. When penetrators strike a target and perforate the skin, the armor spalls into numerous fragments of varying shape, mass, velocity, and orientation. However, the existing models all converged on a single, expected-value for the final result, rather than yield statistical distributions of possible outcomes. Some models attempted to calculate the probability of damaging components individually along a particular shotline but said nothing about the probability of damaging components in combination with one another.

- Many of the metrics commonly output by the standard vulnerability models, such as battlefield utility, were not observable by the vehicle assessors. In fact, none of the extant vulnerability models computed directly observable damage or platform capability. Vulnerability models have historically done a poor job of developing metrics that can be observed in the field. The spotlight in vulnerability modeling today focuses on:

  — direct battle damage (i.e., "killed" or nonfunctioning components) and

  — platform capability (the relationship between "killed" components and measurable platform function, such as rate-of-gun fire, top speed, etc.).

  Battlefield utility, which is not an observable, is now seen to be the proper province of the force-on-force modeler.

- There is a dearth of information concerning many of the mechanisms of physical damage from ballistic interactions.

- There are many ballistic mechanisms that can cause significant damage but are not modeled at all. These typically included blast, shock, fire and toxic fumes.

Thus in 1985, *SQuASH* (for Stochastic Quantitative Analysis of System Hierarchies) [Deitz & Ozolins 1988] was created to fill this void in V/L methodology. Three principles were adhered to in the creation of this model:

- The target description must be *high-resolution* so that components such as wires and hydraulic lines are modeled explicitly.
- The methodology must be *stochastic* in nature to address the fact that many V/L mechanisms are highly sensitive to the initial conditions and respond in a nonlinear fashion.
- The model must output *field observables*, such as damage to components or engineering capability, not simply an expected vehicle loss-of-function.

Thus, the SQuASH model is a stochastic, high-resolution, one-on-one, threat-target computer simulation that uses detailed computer-aided design (CAD) target descriptions to assess the vulnerability of AFVs to direct-fire weapons. SQuASH's submodels account for the nonlinear nature of many types of interactions. For example, the amount of spall when a threat defeats an armor is not a linear function of the hardness of the armor; above a threshold Brinell hardness value, no spall is produced. The precise size, shape, and velocity of spall fragments, for example, are best modeled as a stochastic process. Due to the nonlinear nature of fragment penetration, expected-values for these quantities will not be adequate for determining damage to components. SQuASH output metrics include field observable damage to internal components and remaining engineering capability of the AFV. The primary purpose of SQuASH was, and remains, to provide V/L analysts with a tool to make live-fire pre-shot predictions and to perform post-shot analysis.

The original stand-alone version of SQuASH was coded in FORTRAN. When its predictions were compared to actual LFT, it was found to underpredict component damage [Menne 1987; Dively, *et. al.* 1989; Deitz, *et. al* 1989; IDA 1994; SURVICE 1994]. Significant changes to SQuASH have taken place recently in two areas: improvements to individual algorithms or submodels, and inclusion of the code into the Modular UNIX™–based Vulnerability Estimation Suite (MUVES). The latter is both a computer code for modeling and simulating V/L mechanisms as well as a comprehensive environment for conducting V/L analyses [Hanes, *et. al.* 1991]. We have reason to believe that these changes will have a significant impact on the SQuASH–LFT comparison [Deitz and Saucier 1995]. Consequently, this is an ideal time to plan a verification and validation of the model.

Although no model will ever totally replace testing, it is equally clear that there will never be enough testing to dispense with modeling altogether. A properly accredited model is able to generalize test results by showing where the specific test result lies in the distribution of all possible outcomes. The proper role of SQuASH, then, is to supplement testing by providing insight into specific damage mechanisms. Testing, by itself, does not bring adequate insight. We need to be able to disentangle the individual contributions if we are to understand issues of vulnerability reduction and lethality enhancement.

The remainder of this paper presents our plan for a comprehensive verification and validation of the SQuASH model as it is being incorporated into MUVES. First we present the formal VV&A process, followed by a plan specific to the SQuASH model.

THE VV&A PROCESS

The basic steps in the VV&A process [AR 5-11 1995; DMSO 1995; JTCG/ME 1993] are *verification* of both the underlying mathematical model, as well as its implementation into computer code, and the *validation* of the resulting model, as depicted in Fig 1.

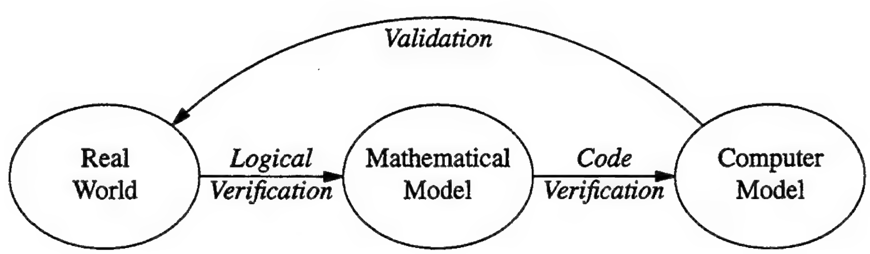


Figure 1. Role of Verification and Validation

These steps are fully documented and given to an ad-hoc Methodology Review Committee (MRC) for *independent review*. The conclusions and recommendations of the MRC are documented and in turn included with the other documentation to form a complete *documentation of the process*. The complete package is then given to an agency that has the authority to make a decision on the *accreditation* of the model. In the following sections, we elaborate upon each of these basic steps in the VV&A process.

Verification

Verification begins with *configuration control*; that is, some group must assume the responsibility for technical and administrative oversight to ensure that the detailed design and computer source code are documented and tracked. *Logical Verification* is the process of verifying that the chosen *mathematical model* is appropriate for the purpose at hand — namely, to serve as an approximation of the real-world phenomenon which is simultaneously solvable and for which the required input data are available. *Code Verification* is the process of finding a *computer model* to implement a solution of the underlying mathematical model. Code verification assures that the code is an accurate translation of the underlying mathematical model. Code verification is performed in a variety of ways including hand calculations, where selected elementary cases are compared. Also, boundary conditions are tested to verify that the model properly handles input that lies outside the intended range. Finally, documentation is checked for completeness and consistency with the source code itself. When this point is reached, *sensitivity analyses* are used to ensure that the model output is sensitive to changes in model input.

Validation

Validation of the model is accomplished through a variety of procedures. *Face validation* is performed by subject-matter experts (SME) who check the model for reasonableness based upon its performance. This is used as a point of departure for a comprehensive validation. *Model assumptions and limitations* are checked to assure that they are appropriate to the phenomena they represent. *Data Audit & Availability* assures that data collection techniques are consistent and well-documented and that the data requirements for the model are realistic. Submodels are compared to results obtained under laboratory conditions. The overall model is also compared to laboratory conditions, where possible, and also to LFT.

Accreditation

The documentation of the verification and validation effort will be turned over to a *Methodology Review Committee* (MRC). This can be an ad-hoc committee, but it must be independent of the M&S developer. The finding of the MRC will be documented and added to all the other documentation. *Accreditation* is an official determination, after review of the complete documentation of the process, that a model is acceptable for a specific purpose. The level of V&V required for accreditation is the amount sufficient for a particular application.

VV&A OF MUVES SQUASH MODEL

In abstract form, V/L methodology in MUVES SQuASH can be considered as three transformations between four distinct spaces, as diagrammed in Fig 2.

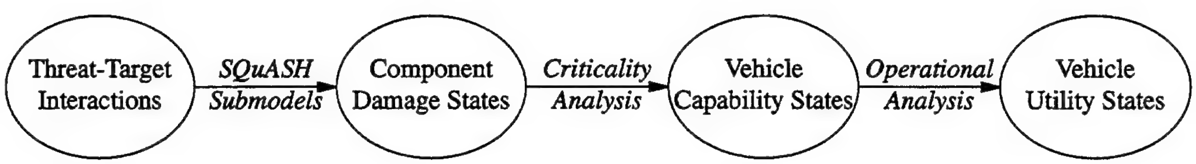


Figure 2. V/L Taxonomy

The V/L Taxonomy [Deitz and Ozolins 1988] was developed to conceptualize this process. The ellipses in this diagram represent four distinct spaces or **Levels**. The arrows represent mapping operators — actually, methodology — that transform information at one **Level** to the next. The following diagram depicts this process in more detail.

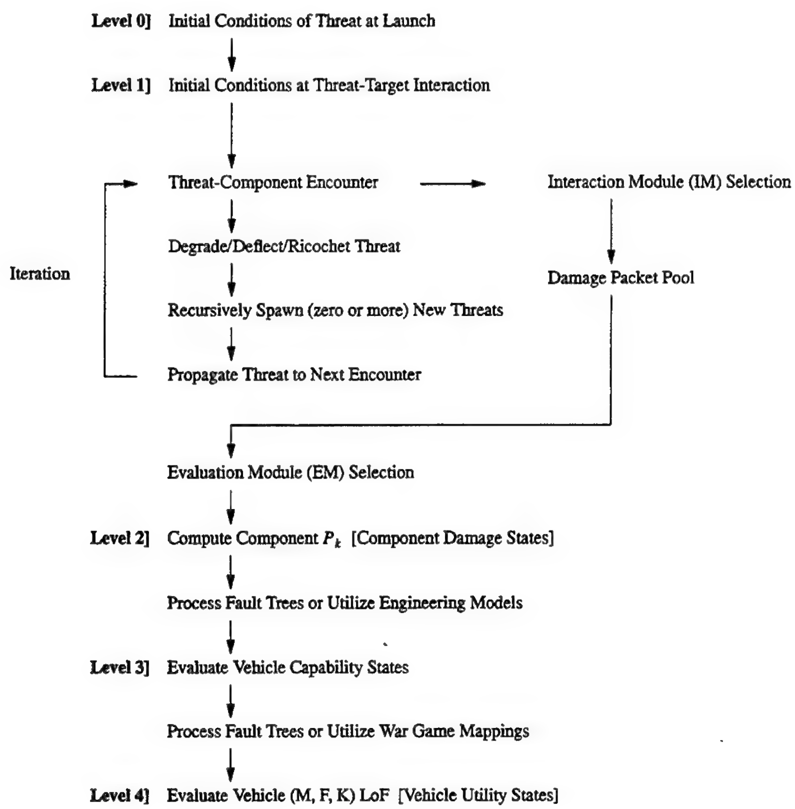


Figure 3. Flowchart of MUVES Methodology

In the case of direct-fire weapons, MUVES begins execution at **Level 1**, as this is typically the information the analyst provides. However, in the case of indirect-fire weapons — an example is artillery (now handled by the SAFE approximation method within MUVES) — execution begins at **Level 0**. At each threat-component interaction, an appropriate Interaction Module (IM) is selected in order to compute the *physical interaction* with the component. However, the *damage* to the component — in terms of whether or not it "survived" the encounter — is not computed at this point in the process. Rather, all of the information to compute the overall damage is placed in a damage packet, which is placed in a queue. Only after all threats (main penetrator, pieces of the broken penetrator, behind-armor debris spall, secondary spall, etc.) have been "played" is the damage packet pool evaluated. Also at each encounter, the threat can be degraded (mass and velocity can decrease), it can be deflected if it perforates the component, or it can ricochet if it is at a high enough obliquity angle. In addition, the threat may spawn new threats by generating secondary spall or pieces due to penetrator breakup. The original (degraded) threat, plus any new threats, are then propagated to the next encounter. It is clear that, in general, there is not a single undeviated path that the threat traverses. MUVES handles this by providing:

- *dynamic ray tracing* (each time a new threat is spawned, it creates a new ray to propagate the threat), and
- *recursive processing* (each new threat is put on the same footing as the original main penetrator).

Each threat continues encountering components until it either comes to rest or it exits the vehicle. After all threats have been processed in this way, the queue of damage packets is sorted by component. The appropriate Evaluation Module (EM) is selected in order to compute the target's functionality or degradation (e.g., the probability of "killing" [P_k] the component). Once all the critical components have been processed (so that the component damage states are known), this information is then passed along to the fault trees. The program then computes the probability of "deactivating" each fault tree by combining all the individual component P_ks. Component P_ks represent the likelihood that a particular component will become dysfunctional given an interaction with a threat. From this combined probability, the program is able to specify the system damage states. It may be at this stage (**Level 3**) or at the next stage (**Level 4**), or a combination of the two, that the Degraded Combat Utility (DCU) in the Damage Assessment List (DAL) enters the computation. This depends upon how the

DAL is constructed. Typically, the DCU values are specified for a combination of critical *components* and for critical *systems*. Finally, knowing the system damage states, the probability of achieving a mobility, firepower, or catastrophic "kill" can be computed. MUVES also provides many post-processing tools for analyzing the program output, but these are not shown in Fig 3.

General MUVES Code

MUVES currently consists of about 330,000 lines of source code. Approximately 85% of the code is in the nature of general utility and not specific vulnerability code — for example, error handling, or memory management. These packages (i.e., logically or functionally related collections of subroutines) have been well tested and are in good shape. The majority of the packages in MUVES have had substantial changes recently or are still evolving. Examples of these would be the Distributions of Random Numbers and the Vector Math packages. The final group of MUVES packages are those that are not yet complete and include the Physical Interaction package and the SQuASH Approximation Method.

There are four procedures that are being employed for code verification:

- *Implementation:* Verify that the code is an accurate translation of the underlying mathematical model.
- *Documentation:* Ensure that the documentation is complete and consistent with the code itself.
- *Test Boundary Conditions:* Verify that the program properly handles input that lies outside its intended range by invoking the appropriate warning or error messages.
- *Verify Explicit Calculations:* Compare selected cases where the answer is known or can be calculated.

SQuASH Submodels

SQuASH submodels carry out the transformation from **Level 1** to **Level 2**, and will undergo verification and validation as stand-alone programs. The following is the list of submodels:

- Armor Penetration
  - Kinetic Energy Rounds
  - Shaped Charge Jets
  - Explosively Formed Penetrators
- Penetrator Breakup
- Ammunition Explosions
- Behind-Armor Debris
- Fragment Penetration, Deflection, and Ricochet
- Component P_k
- Crew Incapacitation
- Hydraulic, Fuel, and Water Lines
- Wire Bundles

These submodels will undergo the aforementioned verification procedures as well as laboratory validation.

SQuASH Overall Model Validation

Once all the submodels are developed, tested, and fully assembled in the SQuASH infrastructure, the overall model will be tested. The idea here is to test the data flow between submodels, check that each submodel has the necessary input, check for possible side effects, and check for methodology gaps in the overall structure. We plan to use both a *bottom-up* and *top-down* approach to model validation. The bottom-up approach will consist of a validation of each submodel as a stand-alone model. The top-down approach will compare the complete model to LFT. Once these have been completed, we will be at **Level 2** (see Fig 2). The mappings to **Level 3** (Criticality Analysis) and **Level 4** (Operational Analysis) are *inputs* as far as MUVES is concerned and are discussed in the next section.

Verification & Validation of SQuASH Inputs

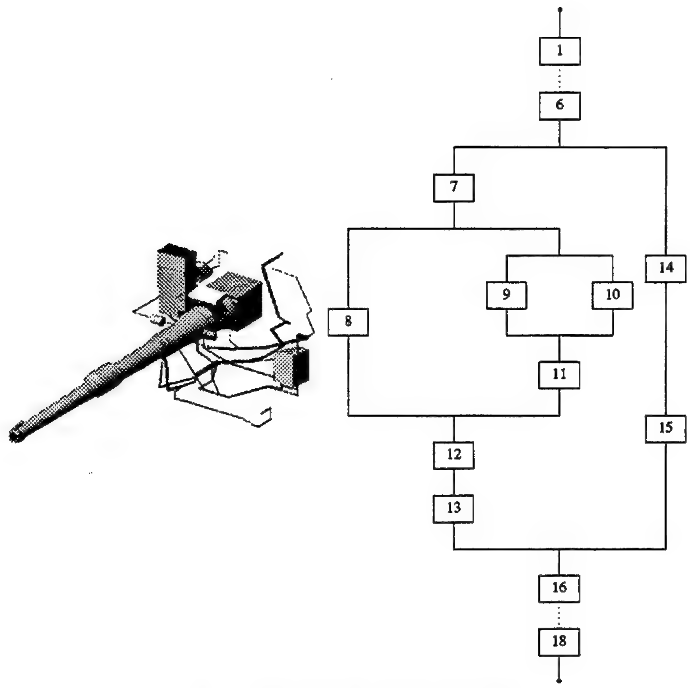
Ordinarily, program input is not a topic for program verification and validation — the cliché is "garbage in, garbage out." In our case, we need to concern ourselves with V&V of input since it is a major part of MUVES. For example, the target description consists of thousands of solids and is very complex. Since the analysis is

worthless if the input is incorrect, we need to V&V the target description. The following areas need to be tested:

- Threats
- Target Description
- Component P_k
- Degraded States, Fault Trees, and Criticality Analysis
- Performance Metrics

Component P_k will most likely be generated off-line with a separate program. The results from this program will then be used to produce tables or functions that will go into SQuASH. The stand-alone program and procedure will need to be verified and validated.

The following diagram (Fig 4) shows all the critical components that constitute the M1A1 Main Armament.



Main Armament Critical Components of M1A1 Tank

ID	*Description*	*ID*	*Description*
1	Main Gun Tube	10	Gunner's Control Handle
2	Main Gun Breech	11	Cable 1W200-9
3	Recoil Mechanism	12	Cable 1W104
4	Recoil Replenisher and Hose	13	Gunner's Primary Sight - Lower Panel
5	Main Gun Trunnions	14	Blasting Machine
6	Turret Networks Box	15	Cable 1W105-9
7	Electric Power - Turret	16	Cable 1W107-9
8	Manual Elevation Pump Handle	17	Cable 1W108-9
9	Commander's Control Handle	18	Main Gun Safety Switch

Figure 4. Fault Tree for Main Armament of M1A1 Tank

If any of these critical components are damaged, then the vehicle will be in some Degraded State (DS). A typical set of DS for an AFV is shown in Fig 5.

Mobility Subsystem		Firepower Subsystem	
M_0	No mobility damage	F_0	No firepower damage
M_1	Slight reduction in maximum speed	F_1	Loss of main armament
M_2	Significant reduction in maximum speed	F_2	Unable to fire on the move
M_3	Stop after time t	F_3	Increased time to fire
M_4	Total immobilization	F_4	Reduced delivery accuracy
M_5	M_1 and M_3	F_5	Loss of secondary armament
M_6	M_2 and M_3	F_6	F_2 and F_3
Crew Subsystem		F_7	F_2 and F_4
C_0	0 crew casualties	F_8	F_3 and F_4
C_1	1 crew casualties	F_9	F_2 and F_3 and F_4
C_2	2 crew casualties	F_{10}	F_2 and F_5
C_3	3 crew casualties	F_{11}	F_3 and F_5
C_4	4 crew casualties	F_{12}	F_4 and F_5
Communication Subsystem		F_{13}	F_2 and F_3 and F_4 and F_5
X_0	No communication damage	F_{14}	F_2 and F_3 and F_5
X_1	No internal communication	F_{15}	F_2 and F_4 and F_5
X_2	No external communication > 300 feet	F_{16}	F_3 and F_4 and F_5
X_3	No external communication	F_{17}	F_1 and F_5 (total loss of firepower)
X_4	X_1 and X_2	**Ammunition Subsystem**	
X_5	X_1 and X_3	K_0	No ammunition lost
Acquisition Subsystem		K_1	Bustle ammunition lost
A_0	No acquisition damage	K_2	Hull ammunition lost
A_1	Reduced acquisition capability	K_3	K_1 and K_2
A_2	Unable to acquire while moving	K_4	K kill
A_3	A_1 and A_2		

Figure 5. Enumeration of Degraded States for an AFV

For an example of a criticality analysis, see [Ploskonka, *et. al.* 1988]. Performance metrics include mobility and fire-power loss-of-function as well as vehicle catastrophic "kill."

STATISTICAL COMPARISON TO LFT

Statistical validation methods used in this portion of the SQuASH validation effort include two procedures that are considered to be judgmental comparisons and an additional two procedures which incorporate hypothesis testing techniques. Judgmental comparisons are widely used. They include graphical analysis and the comparison of common properties, such as the mean and variance of the distribution of the output. They are easy to use and quite practical, but the impact of errors in judgement is difficult to assess. Hypothesis testing includes goodness-of-fit tests, analysis-of-variance techniques, and nonparametric ranking methods; they allow for some degree of confidence in the decision but (as is explained later) require powerful statistical procedures.

We will use two judgmental comparisons to determine whether SQuASH is a valid predictor of component "kill." A separate analysis will be conducted for each live-fire test, although results can be combined to provide more general conclusions concerning the model. In addition, we will conduct two hypothesis tests over all live-fire shots simultaneously, the first to evaluate SQuASH as a predictor of component "kill" and the second to evaluate SQuASH as a predictor of system "kill."

The initial step in hypothesis testing is to state a null hypothesis, in this case "the simulation model is valid." Then a level of confidence is established, often 95%; and a particular test statistic is chosen. Two different errors are present in hypothesis testing. The first is called a Type I error and occurs when a true null hypothesis is rejected. If the level of confidence has been set at 95%, then it follows that the probability of a Type I error is 5%. However, in simulation model validation, a Type II error is the more important to control; this occurs when a false null hypothesis is accepted. No level of confidence is pre-established to guard against accepting an invalid model; but, for any particular statistical test, a measure of the protection against this error is given by the power of the test, equal to the probability of rejecting the null hypothesis when it is, indeed, false.

Unfortunately, there is a tradeoff between the two error types. For a fixed number of observations (sample size), as the level of confidence is increased (lower probability of a Type I error), the power of the test is decreased (higher probability of a Type II error). A Type I error results in the rejection of a valid model — unfortunate, but not as potentially dangerous as accepting an invalid model, the Type II error. Thus, when attempting to validate a simulation model using hypothesis testing, it is imperative that the statistical test be a powerful one.

Box Plots

We will use this graphical method of data analysis to evaluate SQuASH as a predictor of component vulnerability. **Level 2** metrics will be compared on a shot-by-shot basis; results can be grouped by component type and threat type.

For each component and every replication of the model, SQuASH outputs the probability of component "kill." A summary display of the distribution of this random variable can be provided by the box plot [Tukey 1977]. Using this method, the upper and lower quartiles (25th and 75th percentiles) of the data determine the sides of a

rectangle, with the median (50th percentile) portrayed by a vertical line within the rectangle. Dashed lines extend from the ends of the box to the upper and lower adjacent values defined as the largest (smallest) observation less than (greater than) or equal to the upper (lower) quartile plus (minus) 1.5 times the interquartile range. Any observation falling outside the range of the two adjacent values is plotted as an individual point. See Fig 6 for an example of a box plot.

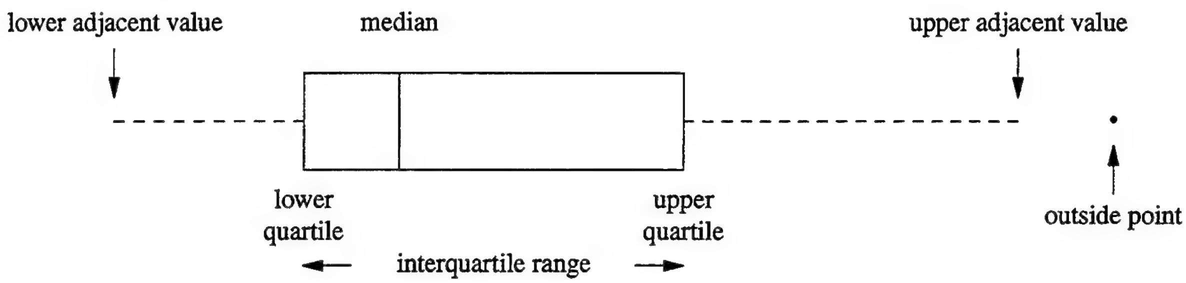


Figure 6. Example of a Box Plot

The box plot provides a quick display of the prominent features of the distribution of component "kill" probabilities. The median shows the location, and the length of the box gives an indication of the spread of the bulk of the data. Outside points allow for the consideration of outliers. The overall plot indicates the degree of symmetry within the distribution. Box plots are useful in situations such as SQuASH output where it is impractical to display all the details of the distribution ("kill" probabilities of each component for every replication).

SQuASH now outputs box plots of the distribution of "kill" probabilities for many critical components. A comparison with the live-fire result ("kill or no kill") will determine whether the field result is an outside point. Realizing many such outside points will reduce confidence in the validity of the model.

Institute for Defense Analyses (IDA) Study

We will use this comparison method of data analysis to evaluate SQuASH as a predictor of component vulnerability. **Level 2** metrics will be compared on a shot-by-shot basis; results can be grouped by component type, threat type, and damage mechanism.

This method was proposed in a briefing prepared by the Institute for Defense Analyses [Turner, Barr, and Okamoto 1994]. From each live-fire test, it requires information on the extent of component damage, as well as the damage mechanism (penetrator, spall, etc.). Damage to critical components is grouped into five categories:

$$
\begin{aligned}
&0.8 < \text{SQuASH } P_k \leq 1.0,\\
&0.6 < \text{SQuASH } P_k \leq 0.8,\\
&0.4 < \text{SQuASH } P_k \leq 0.6,\\
&0.2 < \text{SQuASH } P_k \leq 0.4,\\
&0.0 \leq \text{SQuASH } P_k \leq 0.2.
\end{aligned}
$$

P_ks are then summed within the categories to obtain an expected number of damaged components. These results are presented in histogram form, along with the actual number of complete and partial "kills" obtained from the live-fire test.

Histograms can be prepared for all components simultaneously, or the results can be grouped by system components, by threat types, or by damage mechanisms. The height of the corresponding histograms indicates whether the model underpredicted or overpredicted in each situation. Trends toward one or the other situation reduce confidence in the validity of the model.

Ordering by Probabilities Test

We will use this hypothesis test to evaluate SQuASH as a predictor of component vulnerability. **Level 2** metrics will be compared over all live-fire shots; results can be grouped by threat type and damage mechanism. This test is also applicable to validating the model's ability to predict target perforation.

Let $P = (p_1, p_2, \cdots, p_N)$ be a vector of "kill" probabilities for some component over N live-fire shots. These p_i's represent the mean output probability over M replications of the model. The null hypothesis is that the p_i's are equal to the true probabilities of component "kill" for all N shots, loosely interpreted as "the simulation model is valid." The results from the field test will consist of an N-tuple, the values of which are either 1 or 0

("kill or no kill"). There are 2^N possible combinations of this N-tuple, and its distribution can be obtained by simply considering each combination. The probability of any given N-tuple is equal to the product of the probabilities of the individual elements [p_i if the element is equal to 1, or $(1 - p_i)$ if the element is equal to 0].

Once the probabilities of all 2^N combinations have been evaluated, they are ordered and form the cumulative distribution of P. Assuming a level of confidence of 95%, those outcomes appearing in the bottom 5% of the distribution are considered rare events. If results from the N live-fire shots match one of the outcomes in the tail of the distribution, the null hypothesis is rejected. It is important to remember that with this level of confidence, we would expect even a valid model to produce 1 rejection in every 20 tests. Additional statistical tests could be used to combine these results over a collection of components.

Power studies of this hypothesis test demonstrated better power than that of similar type tests. These efforts, along with an example of the procedure, are provided in a U. S. Army Ballistic Research Laboratory (BRL) report [Webb 1989].

Combination of Independent Mann-Whitney Tests

We will use this hypothesis test to evaluate SQuASH as a predictor of system vulnerability. **Level 4** metrics, values of which range between 0 and 1, will be compared over all live-fire shots; results can be grouped by threat type.

Let $X = (x_1, x_2, \cdots, x_k)$ be a vector of inputs to SQuASH, and let y be an output resulting from X. Then y will take on a value for each replication of the model. Let z be the corresponding value from the live-fire test given the same input vector. In general, y will not be equal to z, since X contains only a finite number of input variables — ostensibly, the most relevant ones. The purpose of SQuASH is to mimic the real-world process. Thus, in attempting to validate it, each empirical value is compared to the corresponding model output generated under the same conditions; that is, the same value for the vector X.

Given M replications, output from the SQuASH model becomes a set of values $y^1, y^2, \cdots, y^M$ for each set of input values which can be compared with (in live-fire testing) a single corresponding empirical value z. Recall that X is a vector of most (but not all) of the relevant input variables. Then z, given X, is a random variable reflecting the random error due to the exclusion of certain factors from X. Also y, of course, is a random variable, since the simulation model is stochastic. We would like to show that $F(y|X)$, the conditional distribution function of y, is equal to $G(z|X)$, the conditional distribution function of z for all $0 \le y, z \le 1$, and for all X.

Considering N different input sets (N live-fire shots), the available data consist of N observations $(y_1^1, y_1^2, \cdots, y_1^M), (y_2^1, y_2^2, \cdots, y_2^M), \cdots, (y_N^1, y_N^2, \cdots, y_N^M)$ of multivariate random variables, where the y^ks for any given observation share a common distribution. Ranking $y_i^1, y_i^2, \cdots, y_i^M$, and z_i for each i provides an indication of SQuASH performance. If the model is valid, the z_i would be expected to fall somewhere in the middle of such a ranking. This is the initial step in a procedure known as the Mann-Whitney test, a particular case in which one of the random variables, namely z_i, has a sample size of one. When we combine N of these tests, we have the null hypothesis of $F(y|X) = G(z|X)$ for all $0 \le y, z \le 1$ and for all X, which we can interpret as "the simulation model is valid."

Let R_i be the rank of z_i in the ith observation $(y_i^1, y_i^2, \cdots, y_i^M, z_i)$; thus, R_i is an integer between 1 and $M + 1$. Then a test statistic T is defined as the sum of the R_i's over all N observations. Very high or very low values of T will cause rejection of the null hypothesis, since this would indicate that the model has a tendency to underpredict or overpredict. The theory behind the Mann-Whitney test is given in most elementary statistics textbooks [Conover 1971], and the properties associated with the combination of such tests have been documented [Van Eltern 1960].

Power studies of this hypothesis test demonstrated reasonable power against appropriate alternate hypotheses. These efforts, along with an example of the procedure, including the derivation of critical values for the test statistic, are provided in a BRL report [Baker and Taylor 1985].

SUMMARY AND PLANS

Modeling has been attacked recently as not providing a credible alternative to LFT. But a properly accredited model has real savings potential. For example, M&S of a radical front-engine design for the M1A2 Tank demonstrated its vulnerability to certain threats — later confirmed by Desert Storm data — with a potential savings of $100M. There is a role for both modeling and testing; it is not a question of one or the other but rather of finding the optimum mix of the two that is most cost-effective to the Army.

The key to establishing the credibility of SQuASH is a comprehensive and properly executed VV&A plan. The plan that we have outlined in this paper will continue to be developed in the upcoming months as we compare the model to laboratory data and LFT.

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This report contains three independent but closely related papers which were written to address a request by Mr. Walter Hollis, Deputy Undersecretary of the Army, Operations Research. Each paper was presented at a symposium in FY96 and was published in the respective symposium proceedings: 1] "A V/L Taxonomy for Analyzing Ballistic Live-Fire Events," 46th Annual Bomb and Warhead Technical Symposium held at Naval Postgraduate School, Monterey, CA, May 13-15, 1996; 2] "Modeling Ballistic Live-Fire Events," 7th Annual TARDEC Symposium, held at Naval Postgraduate School, Monterey, CA, March 26-28, 1996; and 3] "Developments in Modeling Ballistic Live-Fire Events," 16th International Symposium on Ballistics, held in San Francisco, CA, September 23-28, 1996. In combination, this trilogy documents the current state-of-the-art in Army capabilities and specifies the future directions for modeling live-fire events in support of requirements specified in United States Code, Title 10, Section 2366, Chapter 139, National Defense Authorization Act for FY87, "Live Fire Testing."

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